

## Final Report NASA NAGW 186

## CHARGED PARTICLE ALTERATIONS OF SURFACES IN THE SOLAR SYSTEM

PI: R.E. Johnson  
University of Virginia  
Thornton Hall B103  
Charlottesville, VA 22903

## Abstract

The surfaces of "airless" bodies in the solar system are exposed to the ambient plasma, micrometeorites, and the solar UV. The effects of these space weathering agents on surfaces in the solar system has been studied in this project. In the last three years work was carried out on volatile depletion at Mars, on sputtering of the lunar surface, on absorption by implanted S in vapor-deposited H<sub>2</sub>O and its relevance to observations of Europa's surface in the UV, and on the spectral changes produced on irradiating SO<sub>2</sub> and its possible relevance to Io. In addition, the role of plasma-induced charging of E-ring grains was evaluated because of its relevance to E-ring particle source and the lifetime of the E-ring. Finally, the detection of sputtered material from Dione by the CAPS instrument on CASSINI was evaluated as a tool for analysis of satellite surface composition, and the role of sputtering on the ambient OH in the vicinity of the ice satellites and the E-ring was evaluated. Some recent papers: Lunar surface: sputtering and secondary ion mass spectrometry (GRL 18, 2169, 1991); Alteration of the UV-visible reflectance spectra of H<sub>2</sub>O ice by ion bombardment (J.G.R. 96, 17535, 1991); The effect of magnetospheric ion bombardment on the reflectance of Europa's surface (Icarus 100, 534, 1992); Ion bombardment effect on Io's surface (Icarus, 104, 152, 1993); Sputtering, still the dominant source of plasma at Dione? (EosTrans. 74, 572, 1993).

## PROJECT DESCRIPTION

### Introduction

This is a report on a program for the application of laboratory data on the charged particle and UV irradiation-induced modification of materials to the 'weathering' of surfaces of bodies in the solar system. This is one aspect of planetary surface 'weathering'. Since, on objects without a significant atmosphere, micrometeorite and ring-particle bombardment are often competing processes, we have also compared the plasma results to effects produced by those processes.

The radiation and plasma sources of interest are cosmic rays, magnetospheric plasmas, solar plasmas (solar wind, solar flares, etc.), as well as extreme-ultraviolet and ultraviolet radiation. These radiations have been shown to affect the surfaces of a number of objects in the solar system. For instance, sputtering by either ions or by UV radiation probably produces the Na and K clouds on Mercury and the Moon; the surfaces of the natural satellites of Jupiter and Saturn are modified by and are a source of a local plasma; and asteroids, comets, ring particles, and dust can be eroded or modified by the local plasma, the solar plasma, or energetic photons. The magnitude of the effect depends on the nature and intensity of the bombardment, on the chemical composition of the surface, and, on a large object, on the resurfacing rate. Therefore, surface composition can be inferred from the local plasma compositions, resurfacing rates can be determined or constrained from the ion implantation dose, and the sources and amount of the neutral envelope produced by irradiation can be estimated.

An important reason for this work to occur at the University of Virginia is the availability of data from our ion-beam laboratory, and the support from the Materials Science and Engineering Department. Further, we have experience over the last ten years successfully applying such data to volatile depletion on planetary surfaces.

In the last three year period progress has been made toward understanding the UV-visible reflectance spectra of Europa and Io, on developing the analysis necessary to use the plasma instruments on Cassini to study the composition of the icy Saturnian satellites, and on evaluations of the plasma-ion erosion rates for the icy satellites and the E-ring particles. In addition, the charging of the E-ring grains was evaluated, since it bears on their formation and evolution, and aspects of volatile depletion on Mars and the Moon were considered. Papers for the full proposal period are listed at the end.

### Work Completed in Three Year Period

The funding on this proposal averaged only \$32,000 per year over the three year period. In the three year period since the last renewal proposal, the following work was completed and published (see list of published material), supported either completely or in part by this contract:

a) Reflectance Spectra: Because the laboratory reflectance work at Virginia under Boring/Baragiola was not refunded three years ago, the funding given to this contract in the first two years was used to continue the partial support of N. Sack in order that he complete his PhD on that laboratory reflectance project. This lead to continued progress on the UV-Visible reflectance of irradiated water ice (J.G.R. 25, 17535, 1991), and on the effect of sulfur implantation on the UV-Visible reflectance spectra of ice (Icarus 100, 534 1992). The first article shows that fast ion irradiation of ice deposited from a vapor can 'redden' and the second article confirms the long-standing suggestion of Lane et al. and Nelson et al. on the source of

the UV absorption band on Europa's trailing hemisphere. Although preferential venting of SO<sub>2</sub> on Europa's trailing hemisphere could also explain their observations, implantation of sulfur from Io was shown to be a likely source. In a third paper, an SO<sub>2</sub>/H<sub>2</sub>S mixture irradiated with a non-reactive ion gave a spectral ratio after irradiation to that before irradiation which was remarkably similar to Io's trailing/leading hemispheric ratio (Icarus 104, 152, 1993). Again differences in volcanic activity can also explain this ratio but are now not required. The mix used was proposed by Allamondala and co-workers, but agreement could also be obtained by implanting H<sup>+</sup> and S<sup>+</sup> in condensed SO<sub>2</sub> and S<sub>8</sub>.

b) Satellite Surface Composition from Plasma Data: As a participant in the Cassini plasma instrument (CAPS) we have shown that plasma composition measurements can be used to determine the icy satellite surface composition. In the planning and design of the plasma instrument, we insisted on the importance of being able to discriminate molecular from atomic ions. This is needed to detect trace molecular species ejected from the icy surfaces in Saturn's inner magnetosphere (e.g. possibly NH<sub>3</sub> in H<sub>2</sub>O at Enceladus). The ionized vapor to be detected may be due to a number of sources: sputter ejection, micrometeorite bombardment, volcanic ejection, or E-ring particle impact.

In Fig. 1 are shown the sputter products H<sub>2</sub>O, O<sub>2</sub> and H<sub>2</sub> from Dione's surface and the flux of newly created ions from these ejecta were calculated. This flux ions can easily be detected by the CAPS plasma instrument on Cassini, giving the volatile composition of the surface directly. A key measurement which will discriminate plasma erosion from ejection due to micrometeorite or E-ring particle impact is the presence of O<sub>2</sub>, which is a sputter product. Applications to mixed ices have been started.

c) E-ring Charging and Lifetime: E-ring grain charging was suggested by Horanyi et al. to be critical to the orbital history and to the fate of E-ring particles, and was independently suggested by Morfill et al. to be critical for calculating the E-ring grain erosion rate, the supply of neutrals, and the local plasma in Saturn's inner magnetosphere. Therefore, we re-evaluated the charging of the grains caused by UV photons and by plasma ion and electron bombardment of ices, because of the clear errors published in the extrapolation to low electron energies. Appropriate models for the extrapolation were developed based on the physics of electron emission from icy surfaces. These results are fortuitously similar to those of Horanyi et al. This validates the charging used in the E-ring orbit calculations used by Hamilton and Burns, in which the rates for E-ring grain impact of the icy satellites are calculated. They used this to suggest that the E-ring is self-sustaining. The charging levels are much smaller than those required by Morfill et al to cause a significant enhancement in the E-ring erosion rate due to the low energy plasma in the inner magnetosphere. However, other enhancements, which we had discussed earlier, do affect the calculation of the E-ring lifetime and corresponding plasma source rate.

d) Re-evaluation of Saturnian Satellite Sputtering Rates: Earlier we calculated and published lower bounds to the neutral torus density and plasma source rates due to icy satellite sputtering, we showed the E-ring particle sputtering was a smaller source, and we calculated the lifetimes of the E-ring particles. We had also published comments on certain enhancements to these lower limits and recently extended the measurements of the sputtering of water ice. The exciting measurements of an OH density in the region between Enceladus and Tethys (closer to Tethys)

encouraged us to bring these results together. Shemansky et al. stated they found a much larger OH density than predicted by our satellite sputtering model. Using their more recent ionization and dissociation data, our earlier sputter source rates produced  $\sim 1.5$  times the OH suggested, still leaving a large factor. Since this provides a test of plasma effect on the satellites and rings corrections to the lower bounds were estimated:

- 1) Because the icy satellite surfaces are porous we had ignored the angular enhancement in the yield which gives a factor  $\sim 5$  increase on a non-porous surface. [In fact, we have determined the porosity now of our laboratory samples (to be published).] Although this is probably appropriate for a satellite regolith, the E-ring particles are thought to be compact and this enhancement should be included.
- 2) The gyromotion of the ions causes small icy particles to be uniformly irradiated, which we included in our earlier calculations of E-ring erosion. However, if the gyroradius is comparable to the satellite radius, then there is an enhancement in the effective cross sectional area for the satellites. Based on the spatial irradiation profile determined by particle tracking (developed in the previous funding period for determining satellite reflectance changes) we calculated a  $\sim 1.4$  enhancement in the sputter source rates for the icy Saturnian satellites.
- 3) New laboratory data from our group using the dominant sputter ions in Saturn's inner magnetosphere ( $\sim 1\text{-}30$  keV  $\text{O}^+$ ) indicates the onset of the temperature dependence of the sputtering yield starts at a much lower temperature than it does for the earlier measured MeV ions. We ignored such temperature-dependent enhancement earlier. The new measurements give a factor  $\sim 3$  increase in the yield.
- 4) An unsolved issue is the energy distribution of the fastest neutrals ejected by micrometeorite erosion of the rings. The tail of this energy distribution determines the contribution of this process to OH in the region near Enceladus.

The OH sources rates due to sputtering, micrometeorite, and E-ring particle bombardment were compared. For the latter there was an unknown factor, since the recent measurements of craters in ice by Grün et al do not indicate vapor production separately. Based on O'Keefe and Ahrens and data for other systems, the vapor production is very small at the velocities of interest. In the vicinity of Shemansky's OH measurement these sources give a density  $\sim 60$  OH, whereas they suggest  $\sim 180$  OH, a factor of 3 different. This should be considered favorably, since they measure a column of OH from which they estimate a density. As they are obtaining new data and the lab group is extending their measurements, we will continue this comparison as a test of surface reprocessing.

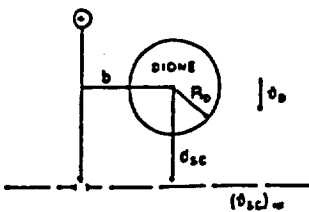
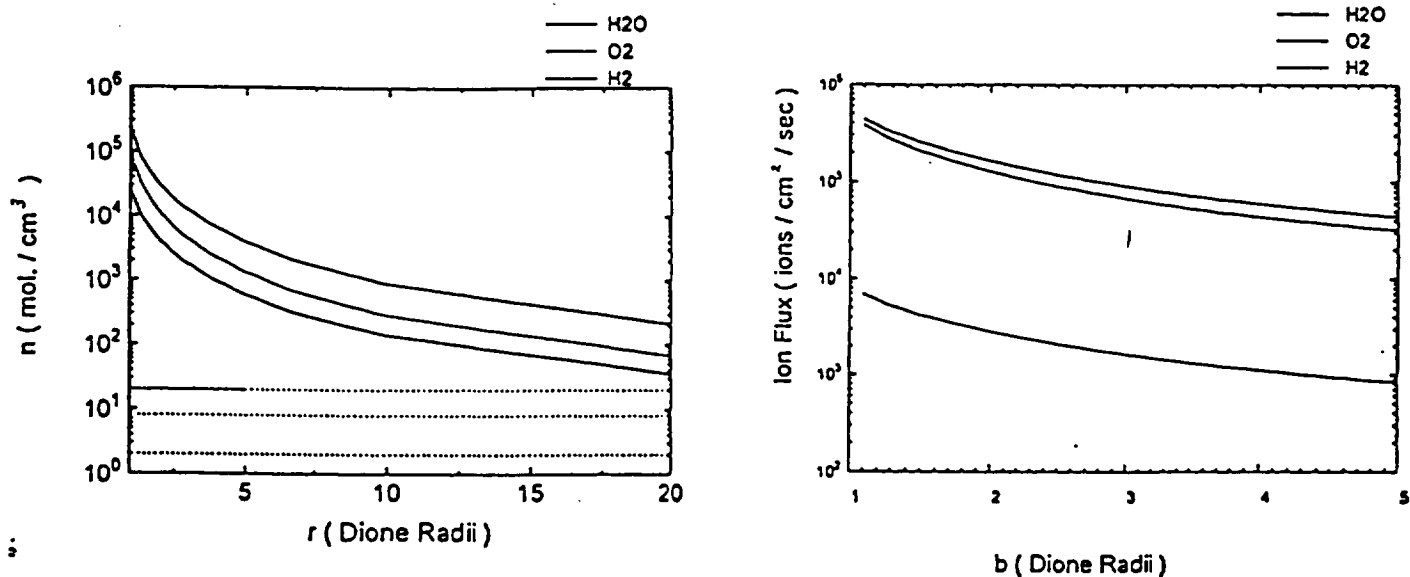
e) Sputtering of Mercury and the Moon: As part of a special issue we re-evaluated the sputtering rates of lunar material (GRL 18, 2169, 1991). The literature is terribly confusing on this because of the different measurements on lunar samples which are used to estimate or to constrain the size of the yield. We showed these each correspond to different 'effective' yields and also showed they were consistent with laboratory measurements on non-porous samples. Further, we predicted the sputter-produced component of ambient lunar atoms (O, Si, Ca, Mg, Fe, etc.).

f) Solar-wind Reddening/Darkening: as part of a collaborative effort with L. Mcfadden at Maryland and her student Gretchin Benedix, rock samples were irradiated at Virginia under UHV conditions to test the hypothesis that the solar wind and solar flares can redden and darken

the rocky materials on asteroids and the moon. Reflectance measurements were made in-situ at Virginia and the samples were taken to Brown for more detailed reflectance studies.

g) Collaborative work was also carried out on volatile depletion from Mars with J. Luhmann, and also with B. Jakosky and R. Pepin. It now appears that pick-up ion sputtering of volatiles from the Martian upper atmosphere, although modest, is important in the competition with surface processes when accounting for the inventory of volatiles expected to have been vented from Mars.

Fig. 1



Publications for full Period of This Contract (1982-present)

- "Erosion of The Galilean Satellite Surfaces by Jovian Magnetosphere Ions," Science (1982).
- "Ice in the Polar Regions of the Moon," JGR (1982).
- "Planetary Applications of Condensed Gas Sputtering," Nucl. Inst. Meth. (1982).
- "Sputtering of SO<sub>2</sub> Frosts: Application to Io," Astrophys. J. (1982).
- "Sputtering of Frozen Gases by Light Ions: Astrophysical Implications," Science, (1982).
- "Thermal and Plasma Induced Molecular Redistributions on the Icy Satellites," Icarus, (1982).
- "Charged-Particle Erosion of Ice Grains and Comets," Astron. Astro., (1983).
- "Plasma-Ion-Induced Molecular Ejection on the Galilean Satellites: Energies of Ejected Molecules," Geo. Res. Let. (1983).
- "Discussion of Energetic Ion Erosion of the Icy Satellites of Saturn Using Voyager Data," J.G.R. (1983).
- "Energetic Charged Particle Erosion of Ice in the Solar System," Chem. Phys. (1983).
- "Erosion and Modification of SO<sub>2</sub> Ice by Ion Bombardment of the Surface of Io," J.G.R. (1984).
- "Production of an Ammonia Depleted Surface Layer," Nature (1984).
- "Sputtering Processes: Erosion and Chemical Change," Adv. Space Res. (1984).
- "Charged Particle Modification of Ices in the Saturnian and Jovian Systems," in Ices in the Solar System, (ed. J. Klinger) (1985).
- "Laboratory Studies of Ion Irradiation of H<sub>2</sub>O, SO<sub>2</sub> and CH<sub>4</sub>" in Ices in the Solar System (ed. J. Klinger) (1985).
- "Sputter Production of S<sub>2</sub> by keV Ions," Comets, Asteroids, and Meteorites II, ed. Rickman et al., (1985).
- "Comment on Evolution of Interplanetary Grains," Ices in the Solar System (ed. J. Klinger) (1986).
- "Ion Bombardment of Interplanetary Dust," Icarus, (1986).
- "Astrophysical Implications for Ice Sputtering," Nucl. Inst. and Meth. (1986).
- "Sputtering of Na on the planet Mercury," Nature, (1986).
- "Sputtering of Sulfur; Application to Io," Icarus, (1987).
- "Radiation Formation of a Non-Volatile Crust on a Comet," Astro and Astro. accepted (1987).
- "Effects of Charged Particles on the Moons and Rings of Uranus," J. Geophys. Res., (1987).
- "Magnetosphere, Exosphere and Surface of Mercury," Icarus (1987).
- "Analysis of Voyager Images of Europa: Plasma Bombardment," Icarus, (1988).
- "Sputtering of Na<sub>2</sub>S and Related Species, Applications to Io," Icarus, (1988).
- "Application of Laboratory Data to the Sputtering of a Planetary Regolith" Icarus (1989).
- "The Effect of Irradiation on the Surface of Pluto" G.R.L. (1989).
- "Magnetospheric Ion Bombardment Profiles of the Icy Satellites: Europa and Dione" Icarus (1989).
- "Effect of Irradiation on the Surface of Pluto" G.R.L. (1989).
- "Application of Laboratory Data to Sputtering of a Regolith" Icarus (1989).
- "Sputtering of the Lunar Regolith", In: Report of the Atmospheric Science Working Group of LexSWG (1990).
- "Sputter-produced Plasma as a Measure of Satellite Surface Composition" GRL (1990).

- "The Primordial Comet Mantle: Irradiation Production of a Stable, Organic Crust" Icarus (1991).
- "Irradiation Effects in a Comet's Outer Layer" JGR (1991).
- "Micrometeorite Erosion of The Main Rings of Saturn as a Source of Plasma" Icarus (1991).
- "Alteration of the UV-visible Reflectance Spectra of H<sub>2</sub>O Ices by Ion Bombardment" I.G.R. (1991).
- "Lunar Surface: Sputtering and Secondary Ion Mass Spectrometry" GRL. (1991).
- "The Effect of Magnetospheric Ion Bombardment on the Reflectance of Europa's Surface." Icarus (1992).
- "Effect of Plasma Ion Bombardment on the Reflectance of Io's Trailing and Leading Hemispheres" Icarus (1993).
- "Rough Stuff at Saturn" Nature (1993)
- "Sputtering, Still the Dominant Source of Plasma at Dione" EOS, Trans. (1993).
- "Charging of Saturn's E-ring Grains" submitted (1994).
- "Magnetospheric Ion Interaction with The Icy Galilean Satellites" review in preparation I.G.R., (1994).
- "Photo Sputtering of H<sub>2</sub>O Ice" Nature (1995).

#### Theses

- Ph.D. Thesis in Engineering Physics. E. Sieveka. May 1983.
- M.S. Thesis in Engineering Physics. L. Barton, May 1984.
- M.S. Thesis in Engineering Physics. T. Cummings, May 1984.
- Ph.D. Thesis in Astronomy. M. McGrath-Kinnaly May 1988.
- M.S. Thesis in Engineering Physics. J. Beaudry 1991
- Ph.D. Thesis in Engineering Physics. N. Sack, 1993.
- Ph.D. Thesis in Engineering Physics. S. Jurac, in progress.

#### Chapters (work supported all or in part by this contract)

- "Interaction of Planetary Magnetospheres with Satellite Surfaces" (with Cheng, Haff, Lanzerotti) in Satellites, eds. J.A. Burns and M.S. Matthews (1986).
- "Magnetospheric Modification of Satellite Atmospheres" (with A. Cheng) in Origins and Evolution of Atmospheres, (Univ. of Ariz. Press) (1987).
- "Irradiation Effects in Comets and Cometary Debris" (with G. Strazzulla) Comets in the Post Halley in press (1990).
- "Irradiation of Solids in Space" in Surfaces in Space (ed. G. Strazzulla and E. Bussoletti) (1991).

#### Book (work supported in part by this contract)

- Charged Particle Bombardment of Atmospheric Gases and Surfaces (1990)

#### Presentations (Abstracts) (1991-1994)

- DPS (Charlottesville)
- DPS (Munich)
- Magnetosphere/ Satellite Interactions (UCLA)
- Io Conference (San Juan Capistrano)
- DPS (Boulder)
- Icy Satellites (San Juan Capistrano)